Quantum Circuits

Period: Spring IV

Prerequisites: Basic knowledge in quantum mechanics including second quantization and harmonic oscillator. Basic knowledge on condensed-matter physics.

Course summary: The physical foundations and implementation of solid-state quantum electronics has attracted broad interest in the context of the realization of quantum information processing systems. In this course, we address the physics of superconducting quantum circuits and show how such circuits can be implemented based on superconducting thin films and nanostructures. We discuss the application of superconducting quantum circuits in quantum information processing systems and in quantum simulation.

The following specific topics will be addressed:

- Josephson effect and Jospehson junction as a circuit element
- systematic quantization of a network of lumped-element electric components such as capacitors, inductors, and Josephson junctions
- classical description of electromagnetics in one-dimension: voltage and current fields
- quantum mechanics of one-dimensional transmission lines and resonators
- cavity-qubit systems and the Jaynes-Cummings model
- operation of superconducting qubits: reset, quantum logic, and readout.
- implementation of quantum gates in quantum computers

Learning outcomes

- Apply the theoretical framework of quantum mechanics in electric circuits and devices, that is, circuit quantum electrodynamics.
- Design and model superconducting quantum circuits: from resonators to qubits
- Identity electrical circuits of practical interest that behave quantum mechanically
- Distinguish between linear and non-linear electronic systems and utilize them for the desired functionalities
- Hypothesize on the behavior of quantum systems

Lectures: 24 h, exercises: 12 h, exam: 3 h + independent work

Grading system: 50% exercises, 50% final exam.

Threshold for passing the course: 50% of assignments in both exercises and exam.

Course outline:

1. **Lecture 1:** ***Key concepts from quantum mechanics and solid-state physics***. Hilbert space, qubits and harmonic oscillators. Quantum mechanics in second quantization formulation. Density of states.
2. **Lecture 2:** ***Components****.* Resistors, capacitors, inductors, filters, lumped-circuit resonators.
3. **Lecture 3:** ***Transmission lines*****.** Physical realization and modeling of transmission lines and waveguides. General models for the propagation of the electromagnetic field. Resonators from transmission lines.
4. **Lecture 4:** ***Introduction to simulation and Multiphysics problems using COMSOL***. Walk around COMSOL desktop; COMSOL geometry; COMSOL physics; results and post-processing of data. Electric field modeling.
5. **Lecture 5:** ***Advanced circuit simulations in COMSOL***. Electro-magnetism, microwave engineerin*g of transmission lines.*
6. **Lecture 6***:* ***Noise in classical and quantum electrical circuits***. Nyquist theorem and the crossover from quantum to classical.
7. **Lecture 7:** ***Superconductivity and the Josephson effect****.* The superconducting order parameter and phase. Tunnel barriers and the Josephson effect. Interference and SQUIDs.
8. **Lecture 8:** ***Quantization of electrical networks***. DiVicenzo criteria and how they are related to this course. Basic concepts: Lagrangian, Legendre transform to Hamiltonian. Example 1: harmonic oscillator. Example 2: an-harmonic oscillator. Example 3: harmonic oscillator coupled to qubit.
9. **Lecture 9:** ***Superconducting quantum bits***. Introducing the transmon qubit, the charge qubit, and the flux qubit. Elements of circuit QED: the Rabi model and the Jaynes-Cummings model.
10. **Lecture 10:** ***Single-qubit operations****.* The transmon: initialization, control and readout. T1 and T2 measurements. Randomized benchmarking.
11. **Lecture 11:** ***Architectures for 2-qubit gates*****.** Realization of: iSWAP, cPhase, and CNOT. Deep dive: Google's quantum supremacy experiment.
12. **Lecture 12:** ***Quantum computing: algorithms and future challenges****.* Overview of VQE and Grover search, scaling, the SW-HW gap, and error-correction

Lectures and topic	Exercises	TA
Lecture 1: **Key concepts from quantum mechanics and solid-state physics**	Ex 1	Suman
Lecture 2: **Components**		Suman
Lecture 3: **Transmission lines**	Ex 2	Suman
Lecture 4: **Introduction to simulation and Multiphysics problems using COMSOL**		Suman
Lecture 5: **Advanced circuit simulations in COMSOL**	Ex 3	Aashish
Lecture 6: **Noise in classical and quantum electrical circuits**		Aashish
Lecture 7: **Superconductivity and the Josephson effect**	Ex 4	Aashish
Lecture 8: **Quantization of electrical networks**		Aashish
Lecture 9: **Superconducting quantum bits**	Ex 5	Aashish
Lecture 10: **Single-qubit operations**		Aashish
Lecture 11**: Architectures for 2-qubit gates**	Ex 6	Suman
Lecture 12: **Quantum computing: algorithms and future challenges**		Suman